

The University of Chicago

THE GENERATION OF
RADIO-FREQUENCY POWER FOR
A CYCLOTRON

A DISSERTATION SUBMITTED TO THE
FACULTY OF THE DIVISION OF THE
PHYSICAL SCIENCES IN CANDIDACY FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF CHEMISTRY

1939

By

SIDNEY L. SIMON

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Introduction

Greater beam energies and larger beam currents can be produced in the cyclotron by increasing the voltage on the "dees." Since this voltage can be shown to be proportional to the square root of the radio-frequency power delivered to the "dee" circuit, it is therefore desirable to increase the power input as much as possible. This may be done by proper choice of the radio frequency equipment and by the selection of optimum operating conditions.

It is the purpose of this paper to show how optimum operating conditions may be chosen for maximum power output and efficiency and how some parts of such a radio-frequency system may be designed for best results.

Description of the Radio-Frequency System in Use Here

The radio-frequency system of which the power triodes and amplifier here discussed are a part is best described by reference to the complete circuit diagram, Figure 1. A three kilowatt (crystal oscillator, power amplifier) exciter supplies the driving power for the large final power amplifier. The exciter unit consists of four stages; a tri-tet crystal oscillator (single 6L6), a 35 watt beam power buffer (single 807), a 300 watt neutralized triode buffer (single 100TH), and a 3000 watt neutralized final (4 HK354 D's in push-pull parallel). A different set of plug-in coils is used for each frequency and another crystal is used if the new frequency is not an harmonic of the old crystal.

CIRCUIT CONSTANTS

R_1 -- 150,000 ohms	$C_{13}-C_{14}$ -- 100 μF per section
R_2 -- 250 ohms	C_{16} -- national NC 150
R_3 -- 30,000 ohms, 20 watts	$C_{17}-C_{18}$ -- 40 μF per section
R_4 -- 4,000 ohms, 100 watts	$C_{19}, C_{28}, C_{30}, C_{31}, C_{38}$ -- .005 μF , 2,500 v., mica
R_5 -- 400 ohms, 400 watts	$C_{26}-C_{27}$ -- 50 μF per section 5,500 v.
R_6 -- 2,100 ohms, 400 watts	C_{32}, C_{33} -- concentric cylinder 8 μF
R_7, R_8 -- 15 ohms, 25 watts, variable	C_{35} -- .001 μF , 7,000 v.
R_9, R_{10} -- 41 ohms, 900 watts, 79 taps	$C_{36}, C_{37}, C_{39}, C_{40}$ -- 200 μF per section, 7,500 v.
R_{11} -- 520 ohms (10-200 watt units)	C_{42} -- .004 μF , 12,500 v., mica
R_{12} -- 50 mv. meter shunt	C_{43}, C_{46} -- .005 μF , 600 v., paper
R_{13} -- 1 megohm, 100 watt	C_{44}, C_{45} -- 40 μF , 20,000 v., concentric cylinder
T_1, T_8, T_6, T_7 -- appropriate fil- ament transformers	$L_1, L_4, L_6, L_7, L_9, L_{10}, L_{16}, L_{21},$ L_{23} -- appropriate coils of copper tubing or wire
T_5 -- 3-4 KVA G.E. 220 v. - 2,200 v.	$L_8, L_{17}, L_{18}, L_{22}$ -- R.F.C.
T_8, T_9 -- 3 KVA, 220 v. - 20 v.	L_{19}, L_{20}, L_{24} -- swinging links of copper tubing or wire
C_1, C_{15} -- .003 μF , 600 v., mica	$L_{25}, L_{26}, L_{27}, L_{28}, L_{29}, L_{30}$ -- 700 turns No. 28 wire, C.T. on 1" x 11" silicon steel core
C_2 -- 350 μF	N_1, N_2, N_3 -- neon lamps
$C_3, C_4, C_5, C_6, C_7, C_8, C_9$ -- .01 μF , 1,000 v., mica	RY_1, RY_2, RY_3 -- relays
C_{10}, C_{34}, C_{41} -- .001 μF , 12,500 v., mica	OR_1, OR_2 -- overload relays
C_{11}, L_2 -- national FXTB unit	
C_{12} -- 75 μF variable	

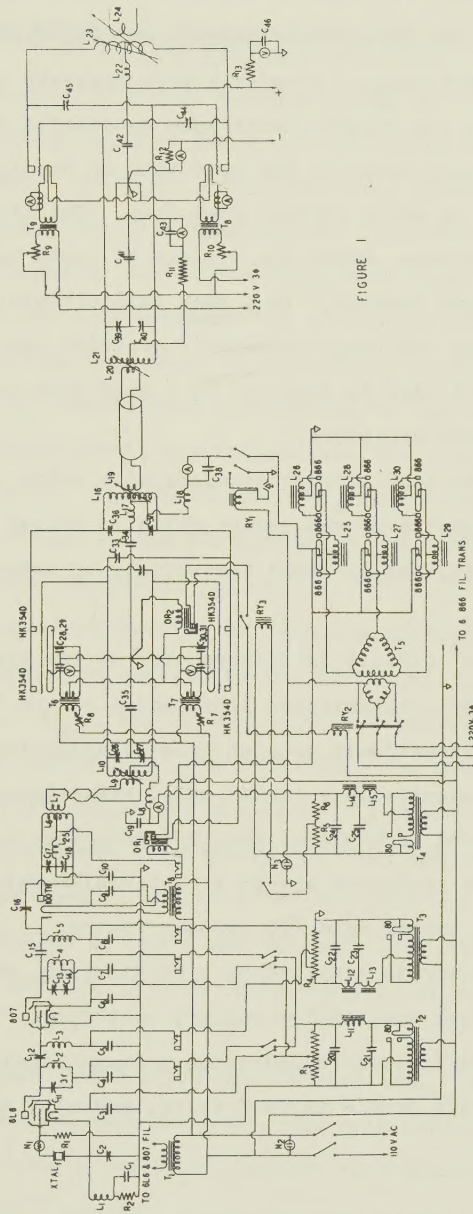


FIGURE 1

The exciter is built in two units, the first containing the crystal and the first three stages, and the second containing the three kilowatt stage. A twisted pair connects this with the preceding stages and three-quarter inch concentric cable carries the radio-frequency power to the grid tank of the final power amplifier which is about fifteen feet away. The final amplifier has two large triodes, which are similar to those described by Sloan, Thorton and Jenkins,¹ in a push pull circuit. This stage is neutralized by two large concentric cylinder type neutralizing condensers. Grid bias is supplied by a grid leak consisting of a number of 200 watt resistors.

The plate tank circuit consists of a water cooled copper coil and the capacity of the bridge which is formed by the neutralizing circuit, and is tuned inductively by means of copper shading disks.

The "dee" circuit is link-coupled to the final power amplifier by a short transmission line tapped on the "dee" circuit at one end and inductively coupled by a swinging link at the other. It is essentially a loaded line, capacitatively loaded by the "dees," and consists of two, 3-inch copper tubes bent at right angles and contained within a rectangular shield box, which also contains a copper vane for vernier tuning.

Plate power is supplied by a 50 kilowatt, three phase power supply which uses twelve mercury rectifiers, type 872 A, fed by six General Electric induction voltage regulators, is continuously variable from 0 to 9500 volts, and will deliver five amperes.

¹Sloan, Thorton and Jenkins, Review of Scientific Instruments, 6, 75 (1935).

Exact Method of Obtaining Operating Conditions
if All the Tube Data Are Known

It is desirable that maximum energy be absorbed by the load impedance and minimum energy be dissipated at the plate of a power amplifier. The plate efficiency of a triode in class C operation is higher than in other methods of operation because maximum current transfer across the tube takes place at a time when the plate voltage is a minimum. In a class C amplifier which employs tubes having a constant amplification factor, μ , the grid bias voltage is greater than corresponds to the cut-off value for the plate voltage and in this ideal case the tube conducts less than half a cycle. The radio-frequency power output is approximately proportional to the plate voltage, if tank circuits are used to preserve the sinusoidal wave.

The important factors in choosing operating conditions are the peak emission current of the filament, I_m , the maximum grid potential, $E_{\max}$, the minimum plate potential, $E_{\min}$, the angle of conduction, θ , and the grid bias, E_c . The power output, power inputs, and efficiencies are determined by these values.

Figure 2 shows graphically how they are related. The case considered here is one in which the grid and plate voltages are 180 degrees out of phase and the tank circuits behave as pure resistances. Current is drawn only when the effective voltage is positive.

All these factors are not independent. Let us assume that the tubes have been designed, the peak emission current is known, and a chart of constant current tube characteristics is available.¹ $E_{\max}$ and $E_{\min}$ should be such as to obtain this peak

¹If the peak emission current is not known, it may easily be calculated by the use of formulas found in any handbook of

emission. Because of the possibility of dynatroning and of excessive current going to the grid, which increases the driving power and reduces the output power, $E_{\max}$ should never exceed $E_{\min}$. Even though smaller $E_{\min}$ means greater plate swing and therefore higher efficiency, it also requires more driving power and a compromise between the two must be made. Common practice is to make $E_{\max}$ equal to $.8E_{\min}$.

If a line is drawn on the characteristic chart (line A in Figure 3) such that the grid voltage is always .8 of the plate voltage, the point of maximum grid and minimum plate volts must lie on this line. Since, also, the peak emission of the tube cannot be exceeded, the operating point should not lie higher on this line than the point at which the total space current, the sum of the grid and plate currents, just equals the peak emission of the filament. It is usually desirable to take advantage of the full possibilities of the filament, so this point determines $E_{\max}$ and $E_{\min}$. The only precaution that must be taken is that the point must not lie in the region where the plate current curves begin to spread, as the spreading is a symptom of incipient saturation and the values of the current curves in this region are uncertain.

The other end of the operating line (B in Figure 3) will lie at a point determined by the voltage of the plate supply and by the grid bias voltage. The plate supply voltage is limited to a fixed upper value by the construction of the supply source, leaving the grid bias voltage as the variable which determines the power output, input and efficiency.

radio engineering, for example, Henney, "Radio Engineering Handbook," 2d ed., The McGraw-Hill Book Co., New York, 1935, pp. 234-38. Methods of obtaining constant current characteristics will be discussed later.

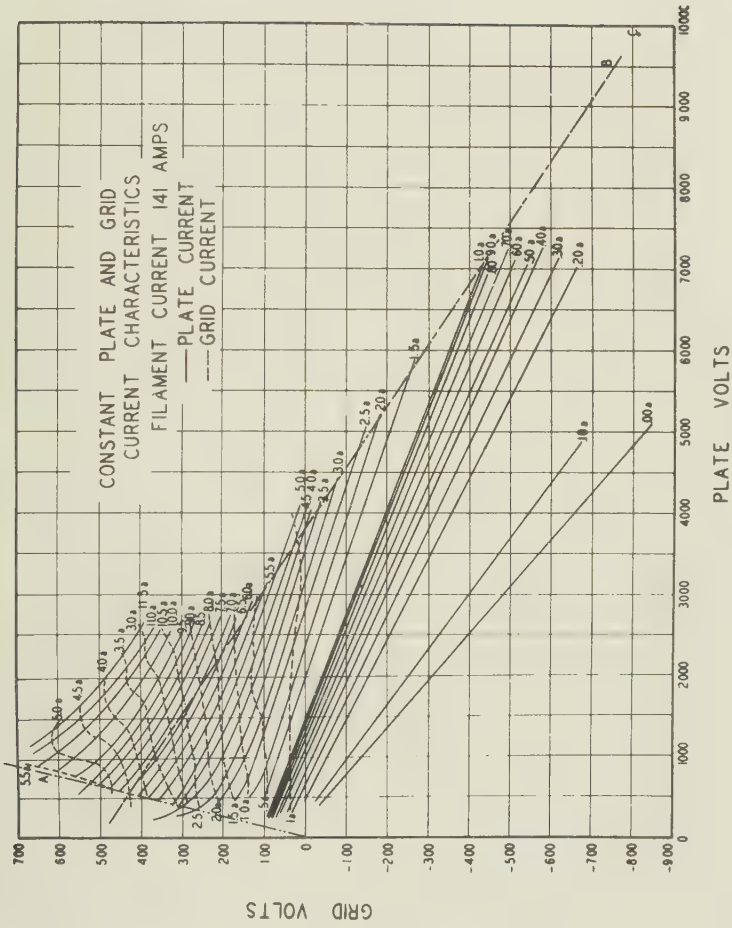


FIGURE 3

The dependency of the operating angle on the grid bias voltage can also be shown by the equation:

$$E_C = \frac{E_B}{\mu_I} + (E_{\max} + \frac{E_{\min}}{\mu_I}) \frac{\cos \frac{\theta}{2}}{1 - \cos \frac{\theta}{2}} - \frac{E_{OI}}{\mu_I (1 - \cos \frac{\theta}{2})} \quad (I)$$

In which:

E_C = grid bias voltage.

E_B = plate supply voltage.

μ_I = amplification factor when the plate current is I.

E_{OI} = the plate voltage when the grid voltage is zero and the plate current is I.¹

This equation is a consequence of the fact that when the plate current is at the value I, the grid and plate voltages are $\frac{\theta}{2}$ degrees away from their peak values. At this point the effective voltage on the tube:

$$\frac{E_B}{\mu_I} - \frac{E_B - E_{\min}}{\mu_I} \cos \frac{\theta}{2} + E_C + (E_{\max} - E_C) \cos \frac{\theta}{2} = \frac{E_{OI}}{\mu_I} \quad (II)$$

For 180° operation the lower end of the operating line will fall on the intersection of the E_p line with the constant current curve for I amperes. (Point C in Figure 3.) For θ 's less than 180° the end of the line will fall at other points on the operating line lying closer to 0 plate volts.

In plotting the current pulses the values of the angles at which the operating line intersects various current lines may be obtained from the ratio of the power supply voltage minus the plate voltage at the point of intersection to the total plate voltage swing ($E_B - E_{\min}$). This ratio is the sine of the desired

¹With the triodes used it was necessary to assume some low value of I (.4 ampere) as effective cut-off because the plate current pulse approaches 0 very slowly and the angular width of the plate current pulse is more closely approximated than by taking the width at actual cut-off.

angle. Plots of these angles against the corresponding grid and plate currents will then give pictures of the plate and grid current pulses. Figure 2 shows these pulses, calculated for the conditions summarized in the first column of Table I.

Averages of these values over a complete cycle are the average plate and grid currents (I_{GDC} and I_{PDC}). If instantaneous values of the currents at various angles of the cycle are multiplied by instantaneous values of the respective voltages at these angles, power curves may be plotted. The area under the grid power curve gives the loss at the grid and that under the plate power curve the plate loss. The values which can be obtained from the power curves are:

$$\text{Total grid driving power} = \text{power loss at grid} - I_{GDC} E_C$$

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power}} = \frac{I_{PDC} E_{BDC} - \text{plate loss}}{I_{PDC} E_{BDC}}$$

$$\text{Power amplification} = \frac{\text{output power}}{\text{total grid driving power}}$$

The values which may be obtained from the current pulse curves are the average plate current I_{PDC} , the average grid current I_{GDC} and the width of the current pulse at effective cut-off. The grid bias voltage is already known so that the value of the grid bias resistor $\frac{E_C}{I_{GDC}}$ and grid bias loss $I_{GDC} E_C$ may also be determined from the known quantities.

Comparison of the values calculated in this manner with the plate power and grid driving power available will show whether they are useful. To choose an optimum set of conditions, calculations corresponding to several angles must be made. If this is done it will be seen that some desirable results are mutually exclusive. Higher plate efficiency often makes necessary higher driving power and although plate efficiency increases with decrease in operating angle, total power output decreases. The

choice of an actual operating condition must therefore be made on the basis of the best possible combination of the important factors for the equipment available.

D. C. Prince¹ gives a method for the choice of operating conditions, if the full characteristics are available which is very similar to the above. After making calculations for several operating angles by a tabular method, he attempts to arrive at a unique optimum set of conditions by plotting output watts against tube loss for three or more different values of the direct current plate potential. He also plots efficiency against power output for these three values and finds the output power for a given tube loss shows a maximum for one plate voltage. The next step is to draw an envelope which includes the points of minimum loss for any particular output. $E_{\max}$, $E_{\min}$, E_C , and grid leak resistance are then plotted as functions of the output for a given tube loss. From this plot the circuit constants for any desired power may be taken, and the efficiency and loss values from the previous curves.

The plotting procedure involved is rather complicated, and the time spent in obtaining equivalent results is probably shorter for the trial and error method first mentioned.

Mouromtseff and Kozanowski also give a method for the choice of operating conditions which is similar to the one used here.²

Approximate and Semi-Approximate Methods

Sometimes data are available in the negative grid region only. In such cases, or where only a crude and qualitative picture

¹Prince, Proc. I. R. E., 11, 275 (1923).

²Mouromtseff and Kozanowski, Proc. I. R. E., 23, 752 (1935).

of the operation of the amplifier is desired, approximate methods may be used. A combination of the exact data for the negative grid region with some method of approximation for the positive grid region will give results of higher precision than those obtained by approximating throughout.

For many of the approximate methods checks have been made with the experimental values which show errors of about 5%, but it must be remembered that agreement as good as this cannot be expected in general.

D. C. Prince gives an approximate method which consists essentially of substituting a portion of a sine wave whose maximum is adjusted to be equal to the peak emission of the tube, for the actual current wave.¹ This may then be integrated mathematically as may similar functions set up for efficiency, loss and output. The values of the integrals are plotted against the angle of conduction and the variation of output with plate voltage can then be plotted. The grid bias may be calculated for a given plate voltage by assuming sinusoidal relationships again.

This method of approximation neglects several important factors, among them the grid current, which may be a large fraction of the space current, the effects of saturation on the upper portion of the current pulse,² and the variation in tube parameters.

An approximate method involving the use of power series and Fourier series for expressing the equation of the tube plate current--plate voltage characteristic was developed by Miller.³ Although it suffers from the same defects of omission as does

¹Prince, *op. cit.*

²Figure 3 shows what happens in an actual case.

³Miller, *Proc. I. R. E.*, 23, 496 (1935).

Prince's method, experimental checks are good.

Everitt¹ assumes a straight line for the I_p - E_p characteristic curves for a triode:

$$I_p = g_m \left(E_G + \frac{E_p}{\mu} \right) \quad \text{for } E_G + \frac{E_p}{\mu} \geq 0$$

$$I_p = 0 \quad \text{for } E_G + \frac{E_p}{\mu} < 0$$

where

I_p = plate current.

g_m = mutual conductance of the tube.

E_G = instantaneous value of the grid voltage.

E_p = instantaneous value of the plate voltage.

μ = amplification factor of the tube (which is assumed constant).

and shows that an assumption of this sort gives a characteristic which is approximately the experimental curve obtained for a type '10 tube. Saturation is neglected but the results must be examined later to see that it is not exceeded. The justification for the assumption of the linear characteristic is the fact that the linearity of class B amplifiers depends on the degree to which the approximation holds good, and they are practically successful. He then assumes that:

$$I_p = g_m (E' \cos \theta - E_a) \quad (\text{IV})$$

where

E' = amplitude of alternating component of the effective voltage.

$E_a = E_C + \frac{E_p}{\mu}$ = direct component of the effective voltage (assuming μ constant).

I_1 , the amplitude of the fundamental, alternating component of the

¹Everitt, Proc. I. R. E., 22, 152 (1934).

plate current, is obtained by evaluating the fundamental Fourier coefficient and I_B , the direct current component is obtained similarly. The ratio of these two quantities is shown to be a function of θ , only, and the total plate current, and therefore the circulating tank current is shown to be directly proportional to the alternating grid volts for a constant operating angle. Output power and grid volts equations are then obtained from a combination of the current equations with the sinusoidal voltage equations. These theoretical equations are then plotted against operation parameters so that design data may be taken directly from them for selected values of the plate loss and plate voltage. This method was checked against experimental data for circulating current, output, input, loss and efficiency and agrees in some cases to within a few per cent.

A method which can easily be used for partial approximation is that given by Terman.¹ The ideal triode equation

$$I_P + I_G = K \left(\frac{E_P}{\mu} - E_G \right)^\alpha \quad (V)$$

in which K is a constant, and α is equal to three-halves, is assumed to be valid. A combination of grid and plate volts to draw the peak emission of the filament is chosen from the complete characteristic curves if they are available. If they are not, the value of the effective voltage $\left(\frac{E_P}{\mu} + E_G \right)$ necessary is obtained from the extrapolation of a plot of the logarithm of the space current against the logarithm of the effective volts. The separation of the effective volts for peak emission into grid and plate volts is made by choosing $E_{\max} = .8E_{\min}$ and assuming μ is

¹Terman, "Radio Engineering," 2d ed., The McGraw-Hill Book Co., 1937, pp. 324-28.

Terman and Roake, Proc. I. R. E., 24, 620 (1936).

Terman and Ferns, Proc. I. R. E., 22, 359 (1934).

a constant in the positive grid region, equal to the highest value of μ obtained in the negative grid region.

The angle of conduction, θ , is chosen somewhere between 120 and 150 degrees, where it has been found by experience most useful choices lie. It is also possible from a knowledge of the ratio of peak to average plate current, which can be calculated from the peak filament emission and the allowable average current drain of the power supply, to obtain a value of the angle conduction from a chart given by Terman.¹ The grid bias voltage for this angle is obtained from Equation (I).

The chart mentioned also gives the fundamental and direct current components of the space current. The separation of these into grid and plate currents is obtained by the approximation, shown empirically to be permissible, that I_{GDC} is about 20% of the total space current and that I_{GAC} is about twice I_{GDC} .² The power input, output and load resistance may then be evaluated directly from these values.

Methods of approximation, of which those above are a representative selection, suffer in general from more or less arbitrary assumptions which must always be made. These assumptions fall into one of the following classes:³

- (1) Current pulses may be represented by some simple equation.
- (2) Amplification factor, μ , is constant.

¹Terman, "Radio Engineering," 2d ed., The McGraw-Hill Book Co., New York, 1937, p. 325. The chart depends on the fact that the direct and fundamental currents are functions only of θ , I_M and α , if equation (V) holds.

²Terman and Ferns, op. cit.; Thomas, Proc. I. R. E., 21, 1134 (1933).

³These assumptions are not all independent.

- (3) Grid current may be neglected or assumed to be an arbitrary fraction of the total space current.
- (4) Secondary emission from the grid may be neglected.
- (5) Characteristic curves may be represented by a simple equation.

Complete characteristic data eliminate the need for approximate methods and for these assumptions, which completely fail to represent the facts in the high current regions where most energy transfer takes place and where therefore an accurate analysis is most important.

Methods for Obtaining Tube Data

It has been shown that complete data are necessary for an accurate analysis of tube performance. The form in which the data are to be plotted is of importance for convenience in use. Constant current curves, expressing the relation between grid and plate volts for chosen constant values of the plate current are most convenient because plate and grid characteristics are on the same chart, the operating line (which is a trace of all conditions of the tube throughout a current pulse) is a straight line and easily located on the chart, and the inverted slope of any constant current line gives the amplification factor for that value of the current directly.

For the negative grid regions, characteristics of this sort are comparatively easy to obtain since the allowable power dissipation for the plate and grid is not exceeded over the major part of the region. It is essential, however, that the plate power supply and bias supply deliver pure D.C. voltages over the entire region. The process consists only of varying plate and grid voltages until the chosen values of plate current are obtained and reading the plate and grid voltages and plate and grid

currents from standard direct current meters placed in the circuits. No grid current is drawn, so the bias supply need not have a large capacity.

In the positive grid regions, however, it is necessary to dissipate amounts of power at the plate and grid which are dissipated for only a fraction of a cycle in normal operation. It is also necessary to supply steadily the large currents needed for the grid and the plate.

It is therefore necessary to use a method of measurement which subjects the tube and power supplies to these loads for only such length of time that their average capacities are not exceeded. One method for doing this was developed by Kozanowski and Mouromtseff.¹ A high voltage, large capacity condenser is charged to any desired potential difference, and is then discharged through a resistor in parallel with the grid and filament of the triode. The voltage drop across suitable non-inductive resistors in the circuit is put on the deflecting plates of an oscillograph. A photograph of the trace produced as the condenser discharges then gives a permanent record of the plate and grid currents and of the plate and grid voltages for a continuous range of grid voltages from the original condenser voltage to zero.

Six exposures by this method give a complete record of the tube characteristics. Experimental difficulties involved are the synchronization of sweep mechanism with the discharge switch and with the camera, and the calibration of the oscillograph which must be a mechanical type in order to record all traces at once on the same film. A major difficulty of the method is the necessity for obtaining a condenser of sufficient capacity and voltage rating, since for tubes rated at only 500 watts, 100 μ F

¹Kozanowski and Mouromtseff, Proc. I. R. E., 21, 1085 (1933)

of 400 volt capacity is needed. It is also difficult to maintain the plate power supply voltage sufficiently constant for the period of the discharge.

Overload of the tube is also avoided in a method given by Terman.¹ In this method the grid is biased far beyond cut-off, 60 cycle A. C. excitation is used on the grid and the ordinary plate supply voltage is used for the plate. The grid and plate currents are read by measuring the deflection produced on a cathode ray oscillograph screen by the voltage drop in the corresponding resistor. A trough vacuum tube voltmeter is used for measuring the plate voltage because a dip in the plate voltage occurs when the current pulse passes, and a peak vacuum tube voltmeter measures the grid voltage.

This method was tried first because it eliminates the difficulties of the condenser discharge method. The plate voltage was measured on the cathode ray oscillograph because a trough voltmeter was not available. The cathode ray oscillograph was used as a null instrument and the voltage pulses after being rectified by a 6H6 rectifier were balanced out by a potentiometer circuit until the pulse entirely disappeared from the oscillograph screen. The bias supply used was the 1500 volt plate supply of the 3 kilowatt final amplifier of the exciter (see Figure 1). A three inch screen, cathode ray oscilloscope was used which had a sensitivity of 2.6 v/mm. with the voltage to be measured applied directly to the vertical deflecting plates. Excitation for the grid was supplied by a 10 KVA General Electric pole transformer with a rated R.M.S secondary voltage of 2300, which was varied by an auto-transformer in the 110 volt primary.

¹Terman, "Measurements in Radio Engineering," 1st ed., The McGraw-Hill Book Co., New York, pp. 238 and 332.

During the course of measurement, dips in the plate voltage of 35% for voltages above 5000 and as much as 90% for voltages below 500 were found.¹ This effect was not noticeably changed by addition of $16\mu\text{F}$ of high voltage capacity across the plate supply. The unusual forms of the current pulses, some of which even showed double peaks was another undesirable feature. In addition, the peaks of the plate current, grid current and plate voltages did not fall on the same vertical line on the cathode ray oscillograph screen. This made it necessary to read values from the intersection of the pulse with this vertical line which introduced a large experimental error, since in many cases the intersection fell on an extremely steep portion of the pulse. Since the grid voltages were read on a peak vacuum tube voltmeter the question of the simultaneity of these values with the others still remained as a probable source of error. The irregularities and inconsistencies of the constant current curves when they were plotted can probably be accounted for by these sources of error.

The weaknesses discussed above were finally eliminated by a measuring method suggested by a method of Chaffee.² The circuit used is shown in Figure 4. In this method the D. C. plate supply was eliminated and A. C. supply (T_2) substituted. All four values, plate and grid current and plate and grid voltage were placed successively on the oscillograph plates by switching to the proper resistor elements (R_1, R_2, R_3, R_4) and there was no difficulty in reading simultaneous values. Bias for the positive grid regions was supplied by a 200 volt D. C. generator (A) whose voltage could be controlled by a resistor in the field windings,

¹Although our power supply was particularly bad in this respect, the effect exists to some degree in all power supplies.

²Chaffee, Electronics, 11, 34 (June, 1938).

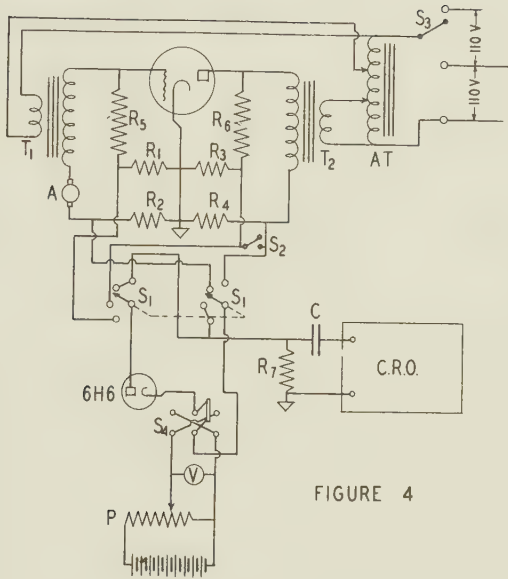


FIGURE 4

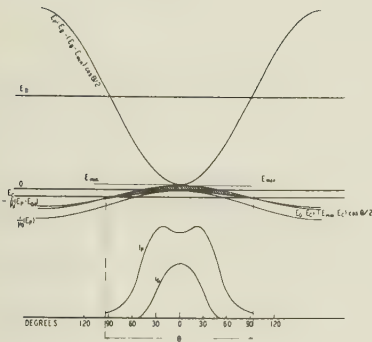


FIGURE 2

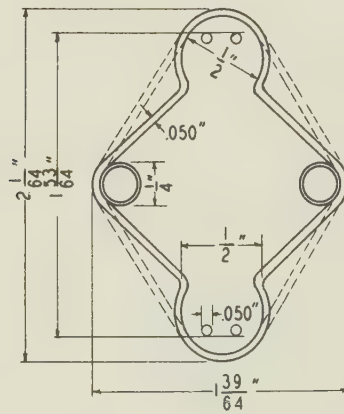


FIGURE 5

and for the negative regions by a 2000 volt, 250 milli-ampere power supply (A) whose voltage was controlled by a Variac in the primary of the high voltage transformer. The oscillograph used has been described. The potentiometer circuit consisted of a wire wound, General radio potentiometer (P) and a Weston D. C. voltmeter.

The method used in making the readings was as follows: A table was drawn up giving the values of the $I_p R$ drops in the plate current resistor for the values of the plate current to be used in plotting. The plate current pulse was then put on the oscillograph by means of the 4-contact, 2-gang switch (S_1). The potentiometer voltmeter was set to the desired value of $I_p R$ and the pulse appearing on the screen balanced out by adjustment of the triode grid bias voltage. This fixed the plate current at the desired value. The other pulses were then put on the screen and determined with the potentiometer voltmeter. This complete procedure was repeated for the higher values of $I_p R$ until the bias voltage could no longer be lowered sufficiently, when the autotransformer (AT) was changed to give different values of the excitation voltages.

It was found that a helpful procedure in avoiding excessive duplication of points (some of which is inevitable in this procedure) was to plot the points immediately after reading a series of values and using the position of the points on the chart as a guide for further adjustments. A total of 312 points was taken and plotted.

In order to obtain constant grid current values to plot on the same diagram, it was necessary to plot grid currents against grid volts for the constant values of the plate current. From this plot, values of grid volts and plate current for chosen

constant values of the grid current were read and plotted on the constant plate current chart, completing the characteristic data needed for a complete and exact determination of the operating conditions of the triode.

Discussion of Data

The constant current curves obtained by plotting the data are shown in Figure 2. An interesting feature is the spreading out of the plate curves from about 9 amperes up to 11.5 amperes, which may be attributed to saturation, since in this region the sum of plate and grid currents exceed the calculated peak emission current from the filament. The grid current curves show this spreading out and also show a broad peak which becomes higher for higher values of the grid current. The slopes of the curves, and therefore the μ 's for the corresponding current values, vary in a regular manner from a minimum at 0 amperes plate current to a maximum at about 5 amperes and down again for higher values of the plate current.

Because of the extremely low μ at cut-off, a reasonable operating angle cannot be chosen to make the plate current zero at the value of the angle chosen. Instead, an effective operating angle must be taken which uses a low value of the current I_p as effective cut-off. Small currents may therefore flow through a large part of the cycle with a corresponding decrease in efficiency.

To eliminate this undesirable decrease in efficiency it is necessary to redesign the tube so as to make μ more nearly constant. The variation in μ may be attributed mostly to the design of the grid and is highly undesirable. It has also been found that the original unsymmetrical design of the grid¹ gave rise to

¹Sloan, Thorton and Jenkins, op. cit. Also see Figure 5, dotted lines.

beaming which causes uneven heating of the plate, as shown by bumping of the cooling water and uneven carbonization of the plate. Since overheated sections of the plate cause gassiness, the beaming was eliminated by bending the grid wires as shown in Figure 5, so as to make the grid more symmetrical with respect to the filaments. After this change, bumping which had occurred at 12 kilowatts plate dissipation did not appear even at 16 kilowatts. In order to secure a more complete cut-off it was also necessary to extend the grid winding to shield a section of the filaments which is left uncovered in the original design

Results

The performances calculated for six sets of operating parameters are shown in Table I. For purposes of comparison the seventh column shows the performance calculated for the initial conditions corresponding to column 1, by a semi-approximation method. For this calculation, it was assumed that only the constant current curves from 0 to 4.5 amperes were available, and Terman's approximate method was used for the remaining regions.

The seventh column of Table I shows how closely one may expect approximate methods to check with the actual facts which are represented by column 1. Corresponding values for average plate current, power output and power input check very well but the remaining values are badly off. Considering the arbitrary nature of the assumptions made, it is surprising that the percentage of error is so low.

The choice between the six exact calculations was made somewhat as follows: Conditions 2 and 6 were eliminated because of the extremely low power output even though they had relatively high efficiency; condition 5 was eliminated because the large grid driving power required was not available. Condition 3 gives

TABLE I
RESULTS OF PERFORMANCE CALCULATIONS FOR SEVERAL OPERATING ANGLES

	1	2	3	4	5	6	γ^*
Voltage of plate supply, E_b	9,500	9,500	9,500	9,500	9,500	9,500	9,500
Minimum plate voltage, E_{min}	550	670	600	550	670	570	495
Maximum grid voltage, E_{max}	430	527	480	430	525	450	396
Grid bias voltage, E_c	756	1,100	890	1,180	1,324	1,160	627
Average plate current, I_{pdc} (amp.) ..	2.32	1.78	2.29	2.42	2.12	1.59	2.5
Average grid current, I_{gdc} (ma.)	727	689	811	863	834	606	440
Power output, P_o (watts)	16,360	14,139	17,213	18,341	16,730	12,679	16,000
Plate power input, P_i (watts)	22,800	16,910	20,587	22,962	20,140	15,105	23,750
Plate efficiency (%)	72.0	83.6	83.6	79.9	83.0	84.0	67.0
Grid loss, P_g (watts)	261	254	414	373	361	220	450
Grid bias loss, (watts)	550	758	722	1,018	1,104	703	276
Grid driving power, (watts)	811	1,012	1,136	1,391	1,465	923	726
Power amplification	18.57	13.97	15.15	13.18	11.4	13.74	22
Overall efficiency (%)	69.3	78.9	79.2	75.3	77.4	78.0	65.4
Bias resistor (ohms)	1,040	1,596	1,097	1,367	1,587	1,915	1,425
Effective operating angle	150°	110°	125°	125°	120°	110°	179°
Width of current pulse at .4 amp. ..	184°	129°	158°	136°	125°	137°	...

*In the calculation by Terman's approximate method (column 7), it was found that the constants of the ideal triode equation which best represented the facts in the positive region were $\alpha = 1.89$, $K = 1.17 \times 10^{-5}$. Previous measurements of the tube with the original grid structure gave $\alpha = 2.2$. For a theoretical triode having concentric cylindrical elements, α should be 1.5.

less output power than 4 and requires less driving power. Since however there is only approximately 200 watts difference in driving power for a difference of 1 kilowatt in the output, 4 is to be preferred. However, condition 1 gives the highest power output for a given grid driving power, that is the highest power amplification. While its efficiency is lower than some of the others, this consideration is outweighed by the other considerations that it gives a large power output, makes use of a reasonable part of the plate power supply capacity and does not require an unreasonable amount of driving power.

When condition 1 was put into effect setting the bias resistor to the required value, an improvement in the performance of the cyclotron was obtained. The voltage of the "dees" as measured by a relative vacuum tube voltmeter increased in the ratio of 7 to 5 and the beam current increased more than 100%.

Summary

1. A method has been developed for measuring tube characteristics far into the positive region with equipment to be found in most laboratories.
2. Data obtained by this method have been used to determine several operating conditions and methods of calculating these conditions from the data are discussed.
3. Grid driving power has been accurately determined and this is of considerable importance in the proper selection of operating conditions to meet any set of requirements.
4. An improvement in the cyclotron performance has been brought about by the application of these methods, which could have been obtained otherwise only by the use of higher powered equipment operated at a lower efficiency.

